EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 667

PERFORMANCE OF A CRYOGENIC VACUUM SYSTEM (COLDEX) WITH A LHC TYPE PROTON BEAM

V. Baglin, I.R. Collins and B. Jenninger

Abstract

The cold bore experiment (COLDEX) installed in the Super Proton Synchrotron (SPS) has been used to study the performance of a vacuum system operating at cryogenic temperatures in the presence of a Large Hadron Collider (LHC) type proton beam. The ~ 2 m long cryostat, which can be cooled below 3 K, is fitted with an actively cooled beam screen which can bee temperature-controlled between 5 and 100 K. Molecular desorption and deposited heat load measurements, with or without gas pre-condensation, have been performed. Implications to the LHC design and operation will be discussed.

CERN, Accelerator Technology Division, Geneva, Switzerland

Paper presented at the 8th European Vacuum Conference
23 - 26 June 2003, Berlin, Germany

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 25 August 2003

Performance of a Cryogenic Vacuum System (COLDEX) with a LHC Type Proton Beam

V. Baglin, I.R. Collins and B. Jenninger

CERN, 1211 Geneva 23, Switzerland.

Abstract

The cold bore experiment (COLDEX) installed in the Super Proton Synchrotron (SPS) has been used to study the performance of a vacuum system operating at cryogenic temperatures in the presence of a Large Hadron Collider (LHC) type proton beam. The ~ 2 m long cryostat, which can be cooled below 3 K, is fitted with an actively cooled beam screen which can be temperature-controlled between 5 and 100 K. Molecular desorption and deposited heat load measurements, with or without gas pre-condensation, have been performed. Implications to the LHC design and operation will be discussed.

1. Introduction

The Large Hadron Collider (LHC), presently under construction at CERN, will mainly collide protons beams at 14 TeV in the centre of mass energy. The twin-aperture machine will be installed inside the existing 26.7 km LEP tunnel and will operate at 1.9 K [1]. In the cryogenic elements, such as dipoles and quadrupoles, the beam circulates inside a perforated 'beam screen' (BS) operating between 5-20 K. The BS perforation and the operating temperature ensure vacuum stability. Gas desorption induced by synchrotron radiation (SR), ions and electrons perturb the beam vacuum [2]. The BS is designed to intercept the beam induced heat loads, thereby avoiding dissipation in the 1.9 K cold bore (CB). The main sources of heat load onto the BS are SR, beam image current and 'electron cloud'. At nominal operation, the expected heat load in the dipole magnets are the SR power ~ 0.18 W/m, the image current ~ 0.15 W/m and the 'electron cloud' ~ 0.22 W/m (~ 1.9 W/m in the field free regions such as interconnects). In addition, the beam losses by nuclear scattering on the residual gas generates a continuous loss of ~ 0.1 W/m for the 2 beams onto the 1.9 K cold mass [3]. These values are constrained within the installed cooling power available in one LHC cryogenic sector of 1.17 W/m at the 5-20 K level and 0.3 W/m at the 1.9 K level [4].

Interactions of the LHC proton beams with electrons created by photoemission or by gas ionisation, result in an 'electron cloud' due to beam induced electron multipactoring. The electrons in the vacuum chamber are accelerated by the positively charged bunched beam towards the vacuum chamber walls, which produce secondary electrons. This acceleration and creation process leads to a growth of an 'electron cloud'. This phenomenon is driven by beam and vacuum chamber parameters. The most important parameters are bunch density, bunch spacing, secondary electron yield (SEY), photon and electron reflectivity. Recently, this 'electron cloud' has been observed in several machines such as PEP II, KEK-B and the CERN Super Proton Synchrotron (SPS) [5]; Table 1 compares the LHC and SPS beam parameters.

Table 1: LHC and SPS nominal proton beam parameters

	LHC	SPS	
Beam energy (GeV)	7 000	26	450
Bunch length (ns)	0.25	4	1.7
Revolution period (μs)	89	23	
Batch spacing (ns)	-	225	
Beam current (mA)	560	55 / 110 / 165 / 220	
Number of batches	-	1 / 2 / 3 / 4	
Number of bunches	2808	72 / 144 / 216 / 288	
Filling factor (%)	79	9 / 16 / 24 / 31	
Bunch current (protons/bunch)	$1.1\ 10^{11}$		
Bunch spacing (ns)	25		

Since an 'electron cloud' is potentially of major importance for the LHC, the cold bore experiment, COLDEX, was installed into the SPS to study the effects in a cryogenic system.

2. Experimental

The COLDEX cryostat, which has originally been used to study gas desorption induced by SR, has been installed in a vacuum bypass of the SPS [6, 7]. The COLDEX houses a ~ 2.2 m long extruded OFE copper BS inserted into a 316 LN stainless steel CB. The BS's circular holes provide a transparency of 1 %. The BS and CB can be temperature-controlled independently. A dedicated cryoplant provides liquid helium to the experiment.

Two valves placed at the COLDEX extremities isolate the experiment from the SPS vacuum system. When beginning an experiment, the COLDEX is moved into the beam path and the valves are opened. The COLDEX experimental area is ~ 5 m long. The BS and the two ~ 0.3 m long cold/warm transitions (CWT) have an elliptical shape with horizontal and vertical axes of 84 mm and 66 mm respectively. To limit the thermal conduction to the BS, the CWT is made of stainless steel with 0.1 mm thickness. The resistance of each installed CWT, with two RF contacts, is ~ 15 mΩ.

The total and partial pressures are measured in the centre of the BS *via* a room temperature (RT) chimney and at the COLDEX extremities. Calibrated residual gas analysers (RGA) and Bayart-Alpert gauges (BA) are used. Prior to the experiments and with the valves closed, the complete apparatus was baked out to 300°C for 24 hours with the exception of the CWT, BS and CB.

The BS is temperature controlled from 5 to 100 K via circulation of gaseous helium. The BS heat load is measured by the increase of the BS temperature at known helium flow. The thermometers and the flow meter are calibrated. The sensitivity of the heat load measurement is ~ 0.5 W/m. Above 1, 2 and 3 W/m, the maximum relative error is 40, 20 and 15 % respectively.

3. Results

During all the experiments described, the presence of an 'electron cloud' in the SPS was also indicated by other SPS detectors such as electron pick-ups, pressure gauges, strip detectors and calorimeters [5]. The SPS proton energy was 26 GeV except in section 3.3 where a ramp of 450 GeV was applied.

3.1. Long term circulation of a LHC type proton beam

About one day before the experiment, the COLDEX was cooled down. The CB was set to 4.2 K and the BS to 8 K. In the BS centre, the pressure was 1 10^{-9} mbar. A LHC type beam was then circulated through COLDEX. Figure 1 shows the residual gas pressure when, at time 0, a batch of 72 bunches with 8 10^{10} protons/bunch was circulating through COLDEX. A strong pressure increase to 10^{-6} mbar, dominated by H_2 could be observed. This increase could be inferred to the unconditioned state of the BS. Other gases such as CO, CO_2 reach 10^{-8} mbar and CH_4 reaches 10^{-9} mbar. Similarly to SR experiments, there is a slow increase of H_2 pressure up to an equilibrium value [7, 8]. This increase results from the recycling of H_2 molecules previously desorbed and physisorbed onto the BS.

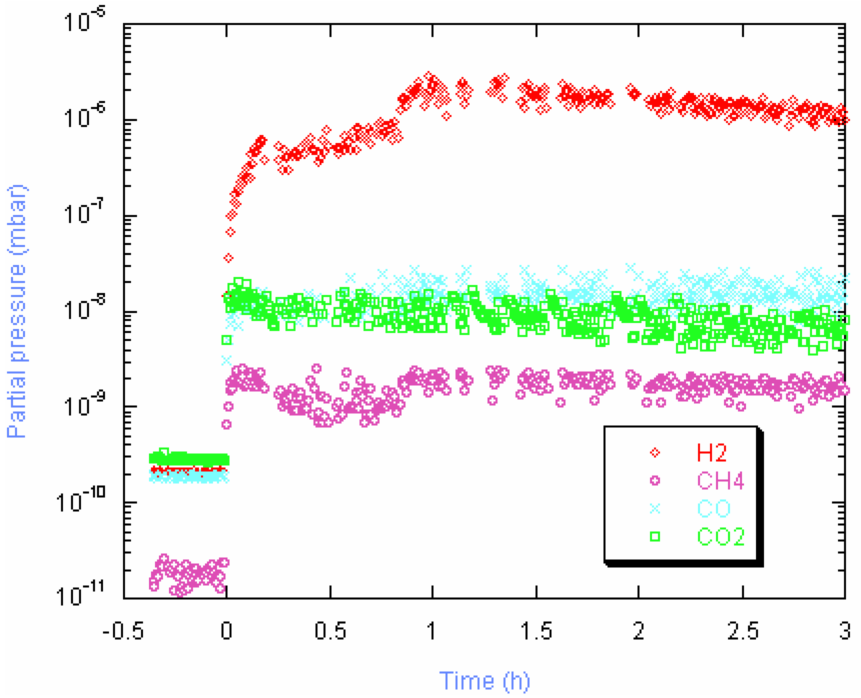

Fig.1. Partial pressure increase with 1 batch of 72 bunches of 8 10^{10} protons/bunch. The BS and CB operate at 8 K and 4.2 K respectively.

Once the recycling desorption is balanced by the BS pumping, an equilibrium pressure results from the pumping of the BS holes and the pumping at extremity. Assuming a mean electron energy of 100 eV, the estimated electron flux, $\dot{\Gamma}$, amounts to 6 10^{16} e/m/s [5]. Given the high gas load, the CB H_2 pumping speed may vanish, the estimated primary electron desorption yield, η, equals $\sim$ 5 10^{-2} H_2/e^-.

Since no increase due to recycling yield, η', of gases other than H_2 is seen in figure 1, only the sum of the primary and recycling yields over the sticking coefficient, σ, could be derived from the pressure rise. Following equation (1), where G equals 2.4 10^{19} molecules/(mbar.l) and S is the BS pumping speed, the values are 2 10^{-2}, 2 10^{-1} and 1 10^{-1} molecules/e^- for CH_4, CO and CO_2 respectively. These preliminary results do not take into account any significant contribution from the chimney or other parasitic desorption which cannot be excluded at this point.

$$\frac{\eta + \eta'}{\sigma} = \frac{G\,S\,\Delta P}{\dot{\Gamma}} \quad . \tag{1}$$

Figure 2 shows the evolution of the total pressure, mainly H_2 content, and of the heat load on the BS as a function of time. For reasons of clarity, data without beam were not shown. During most of the time, 2 batches of 72 bunches each were circulating in the SPS.

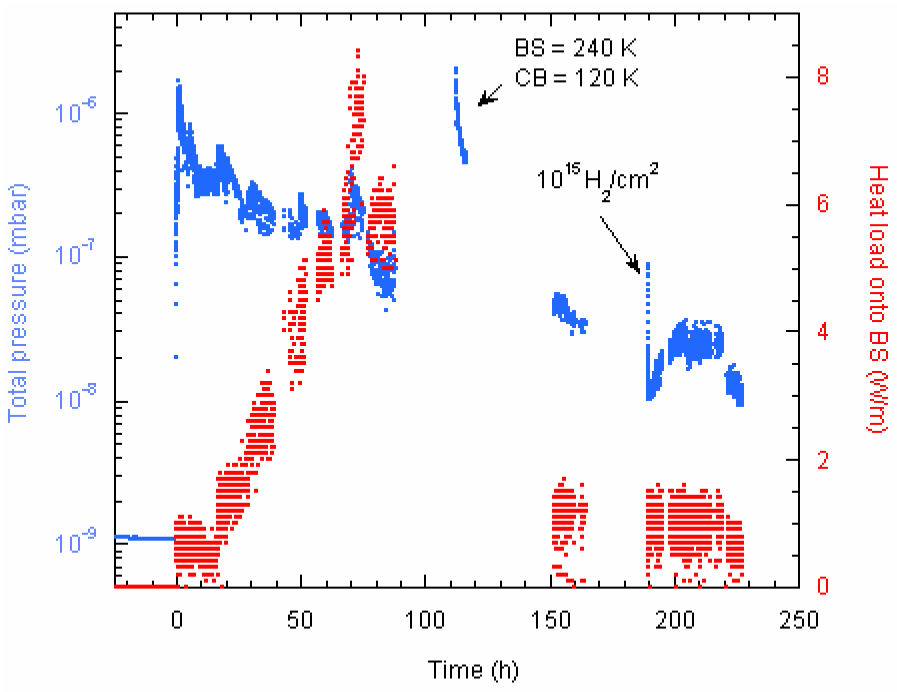

Fig.2. Total pressure and heat load onto the BS as a function of time with 2 batches of 72 bunches with 0.8 to 1.1 10^{11} protons/bunch.

In the first part of the experiment, up to 85 h, the total pressure initially rose to 10^{-6} mbar and decreased, due to beam conditioning, to ~ 7 10^{-8} mbar. Conversely, the heat load deposited onto the BS increased from ~ 0.5 to 6 W/m. This could be attributed to the growth of a condensed gas layer modifying the surface properties and/or to the bunch current increase starting at 0.8 10^{11} and reaching 1.1 10^{11} protons/bunch at 50 h (from 70 to 75 h, 3 batches were circulating which produced ~ 7.5 W/m). After one day, due to the large heat load on COLDEX, the BS and CB temperatures were increased to 20 K; this implies that H_2 was only pumped through the extremities.

In the second part of the experiment, the beam was switched off and the valves at the extremities were closed. The BS and CB were warmed up to 240 K and 120 K respectively. The valves were re-opened, and the LHC beam circulated for 4 h through COLDEX. The conditioning effect is clearly visible in the total pressure which decreased from 10^{-6} mbar to 4 10^{-7} mbar.

At 150 h, the BS and CB were once again cooled down to 10 and 4.2 K respectively. The bunch current was ~ 1.2 10^{11} protons/bunch and the pressure still ~ 4 10^{-8} mbar. However, after the temperature excursion *i.e.* the removal of all gases condensed onto the BS and beam circulation near RT, the heat load deposited onto the BS was reduced to ~ 1 W/m. The beam was then maintained in similar conditions up to 220 h, during which pressure and heat load remained almost constant. At 190 h, an amount of 10^{15} H_2/cm^2 was injected and condensed onto the beam screen prior to beam circulation. With beam, the pressure increased to 9 10^{-8} mbar, as expected, due to H_2 recycling desorption. The estimated recycling desorption yield is ~ 2 10^{-1} H_2/e^-.

At 220 h, a beam with LHC nominal condition was circulating; a final pressure of 10^{-8} mbar and a power of 0.6 W/m were achieved. The corresponding primary electron desorption yield is ~ 10^{-2} H_2/e.

3.2. *Effect of number of batches and bunch current*

The effect of the number of batches and bunch current was investigated from 50 to 75 h in order to minimise any effect related to cleaning. Figure 3 shows the variation of the heat load onto the BS as a function of bunch current for 1 to 3 consecutives batches circulating in the SPS. At 1.1 10^{11} protons/bunch, the heat load is proportional with the number of circulating batches which indicates that the ‘electron cloud’ is saturated within the first few bunches [9]. In agreement with other measurements, a threshold of 4 10^{10} proton/bunch could be derived from the curve fit [5]. The large variation of power observed with the bunch current might explain the heat load increase observed in Figure 2. These observations could be reproduced in simulations [10].

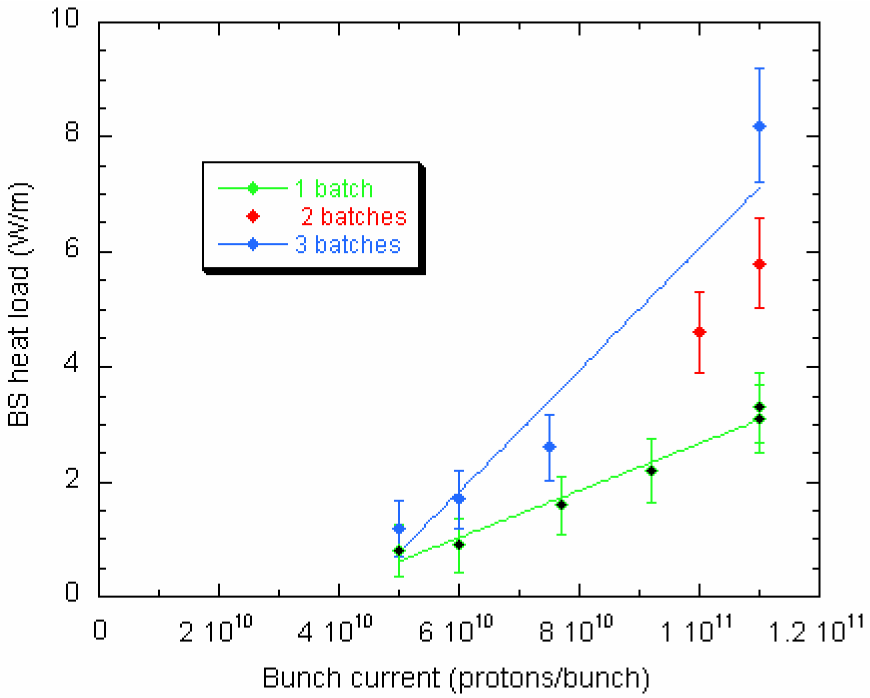

Fig 3 : Heat load onto the BS as a function of bunch current and number of circulating batches measured at t = 50 to 75 h. The BS and CB operated between 10 to 20 K.

3.3. *Effect of condensed gases*

Several experiments were made to investigate further the behaviour of a cryogenic system in presence of an ‘electron cloud’.

a) COLDEX was kept under vacuum (~ 10^{-8} mbar) at RT for 2 months. After cooling down, no significant increase, with respect to Figure 2 at 225h, of the total pressure (10^{-8} mbar) nor the heat load (1 W/m) was noticed while 4 batches of 0.9 10^{11} protons/bunch were circulating

b) Similar observations were made when, while held at RT, COLDEX was vented to air and pumped back before cooling down.

c) COLDEX was kept to atmospheric pressure for 2 weeks and pumped down to 10^{-4} mbar before valving off the turbomolecular pump. Then, the BS was cooled down to 10 K and finally the CB to 3 K. LHC type beams with 2 and 4 batches of 1.1 10^{11} protons/bunch were circulated through COLDEX for 2 days. The heat load deposited onto the BS remained constant at 1 and 2 W/m respectively. During this period, the total pressure was 10^{-8} and 3 10^{-8} mbar. Assuming again 100 eV electron energy, the accumulated dose would have been ~ 10 mC/mm^2 which would be the dose required to scrub a surface, at RT, down to a maximum SEY of ~ 1.2 [11]. It is not clear whether the lack of efficiency for scrubbing could be attributed to the cryogenic environment and/or a low electron energy.

d) Finally, an amount of 6 10^{16} CO/cm^2 were injected and condensed onto the BS at 10 K, while the CB was held at 100 K. When 1 batch with 1.1 10^{11} protons/bunch was circulating, a power of 5 W/m was measured on the BS. This result suggests that the thick layers of condensed gases induce large heat load onto the BS, which could be an explanation for the observations in Figure 2. Any resistive losses in the coaxial space such as high order mode as a source of the heat load onto the BS can be excluded. Due to the difference of the electric resistivity between copper (BS) and stainless steel (CB), a heat load of 0.5 W/m on the BS could have been accompanied by a heat load of 30 W onto the CB, which would not allow to operate the cryoplant [12].

4. Implications for the LHC

All the measurements performed above were carried out with up to 31% filling factor and “long” bunches as compared to LHC. However, within these restrictions and according to the results, a pressure of 10^{-8} mbar, which is the LHC design life time limit, could be reached within a few days of operation. H_2 has been shown to be the dominant gas species. During this period, the heat load onto a calorimeter operating at RT, located upstream of COLDEX, was reduced from 0.2 to 0.02 W/m [13]

A heat load, of up to 6 W/m, could be observed in the cryogenic system. A warming-up of the BS to remove thick layers of condensed gases and beam circulation at high temperature, has been demonstrated to be efficient to reduce the heat load to 1 W/m. Further beam circulation, while operating COLDEX at cryogenic temperature, seemed to be less efficient to reduce the SEY than operation at RT. Thick layers of condensed gas, such as CO, has been shown to induce large heat loads.

A periodic warming-up of the LHC BS, to remove the condensed gases from the inner BS surface, may be a remedy to limit the heat load due to the layers of condensed gases. The operation of the LHC BS at higher temperature while beam is circulating might be a possibility to avoid gas condensation and possibly increase the efficiency of the SEY reduction by scrubbing [14].

5. Conclusions

Preliminary performance of a cryogenic vacuum system made of a BS and a CB technology similar to the LHC exposed to ‘electron cloud’ in the presence of LHC-type proton beams have been investigated. Primary and recycling desorption yields in a cryogenic system have been estimated. The dynamic heat load onto the BS has been shown to be potentially significant. A warming-up of the BS to remove the condensed gas and a beam circulation at high temperature has been shown to be very effective in reducing the dissipated power. Some possible limitations of the scrubbing of a cryogenic vacuum system in a closed geometry, applicable to LHC, have been found. Possible remedies such as warming-up and scrubbing at high temperature have been proposed. At the end of the studied period, for two batches with nominal LHC bunch current and spacing, the vacuum level was 10^{-8} mbar *i.e.* within or close to the LHC beam lifetime limit. At the same time, the measured power deposited on the BS was 0.6 W/m *i.e.* below the budget for the field-free region.

The results presented here should be consolidated in the near future, especially in terms of heat load. A circular BS of 67 mm ID will be installed inside the SPS [14]. This BS has been previously exposed to a SR dose of about 10^{23} photons/m as expected to be prior to the scrubbing period of the LHC commissioning scenario [14]. The accuracy of the heat load measurement will be increased. An in-situ calibration of the heat load will be implemented. Electron detectors will be placed inside COLDEX. A RT calorimeter, of the same material and shape as the BS, will be installed between the valves located at the extremities of the experiment. The aforementioned remedies will be tested to consolidate the LHC scrubbing scenario. The operation at different temperature and effect of condensed gases should be studied in detail.

Acknowledgements

The work performed by NIKHEF during COLDEX design and construction is gratefully acknowledged. We would like to thank G. Arduini, R. Bailey, P. Collier, K. Cornelis as well as the SPS operating team for running the SPS machine with excellent beam quality. The support from R. Wintzer, the SL vacuum team and M. Jimenez is acknowledged. The work carried out by N. Delruelle, O. Pirotte, Y. Drouyer, D. Legrand to refurbish and maintain the helium liquefier is gratefully acknowledged. Fruitful discussions with many colleagues of the Vacuum Group and particularly R. Cimino, O. Gröbner, N. Hilleret and A. Krasnov are acknowledged.

References

[1] The LHC Study Group. The Large Hadron Collider, Conceptual Design, CERN/AC/95-05, 1995.
[2] Gröbner O. Vacuum 60 (2001) 25-34.
[3] Heat load working group, http://lhc-mgt-hlwg.web.cern.ch/lhc-mgt-hlwg/.
[4] Lebrun P. LHC Project Report 629, February 2003.
[5] Jimenez JM, Arduini G, Collier P, Ferioli G, Henrist B, Hilleret N, Jensen L, Laurent J-M, Weiss K, Zimmermann F. LHC Project Report 634, April 2003, submitted to Phys. Rev. ST. Accel. Beams.
[6] Baglin V, Collins IR, Grünhagel C, Gröbner O and Jenninger B. Vacuum 67 (2002) 421-428.
[7] Baglin V, Collins IR, Grünhagel C, Gröbner O and Jenninger B. Proceedings of EPAC 2000, p2283-2285, Vienna, Austria
[8] Calder R, Gröbner O, Mathewson AG, Anashin VV, Dranichnikov A and Malyshev OB. J. Vac. Sci. Technol. A 14(4), 2618, Jul/Aug (1996).

[9] Jimenez JM, Arduini G, Collier P, Ferioli G, Henrist B, Hilleret N, Jensen L, Weiss K, Zimmermann F. LHC Project Report 632, April 2003.
[10] Benedetto E, Schulte D, Zimmermann F. Proceedings of the LHC workshop - Chamonix XII, CERN, Geneva, April 2003.
[11] Baglin V, Collins IR, Grünhagel C, Gröbner O, Henrist B, Hilleret N and Jenninger B. Proceedings of the LHC workshop - Chamonix XI, CERN, Geneva, February 2001.
[12] Vos L, Private communication 4/2/03.
[13] Baglin V, Jenninger B. Phys. Rev. ST. Accel. Beams 6, 063201 (2003).
[14] Baglin V. Proceedings of the LHC workshop - Chamonix XII, CERN, Geneva, April 2003.